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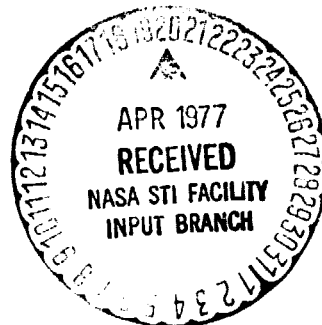
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AND BORON/CARBON FIBERS**

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INTRODUCTION

Although composites made from boron fibers in metal matrices exhibit high strengths compared to many metals, they have in general a much lower ability to absorb impacts. One way that this impact energy absorption can be increased is by increasing the fiber strength since the energy stored in each fiber at fracture is proportional to the square of the fracture stress of the fiber. By measuring the change in fracture stress of 203 μm (8 mils) diameter fibers of boron on tungsten (B/W) as a function of fiber diameter as reduced by chemical etching, Smith (ref. 1) has shown that the flaws which limit B/W fiber strength are located at the surface and in the tungsten boride core. The average fracture strength as limited by surface flaws is 3.59 GN/m² (521 ksi). After etching to a diameter of 188 μm virtually all fiber fractures were caused by core flaws, the average strength being 4.50 GN/m². If both the surface and core flaws are removed, the fracture strength, limited by flaws in the boron itself, is approximately 6.89 GN/m² (ref. 2). This was measured on B/W fibers which had been split longitudinally and had their cores removed by chemical etching. These data indicate that it should be possible to increase the fiber strength by a large amount before one is limited by the bulk flaws.

Because the limiting flaws are located at the surface and in the core, it is important to know what the residual stresses are in these fibers particularly at the limiting flaw locations. Measurements have shown that the residual stresses at these locations are compressive for B/W fibers (refs. 3, 4, 5). More recent measurements (ref. 6) made on 203, 142, and 102 μm B/W fibers have yielded the longitudinal residual stress distribution with radius, from the surface to near the core. Also, in the case of the 102 μm fiber, the average core stress was determined.

In this investigation the longitudinal residual stress distribution was determined for 102 μm diameter B/W and B/C fibers.

EXPERIMENTAL

The fibers studied in this investigation were made by AVCO Systems Division. The 102 μm diameter B/W fibers were deposited on a 12.7 μm diameter tungsten wire resistively heated in a $\text{BCl}_3 - \text{H}_2$ reactor. The 102 μm diameter B/C fibers were made by the deposition of boron on a pyrolytic graphite coated carbon fiber (ref. 7). The deposition process produces an elongation of the growing fiber which, in the case of B/W, is closely matched by the expansion of the tungsten lattice due to the boriding of the tungsten wire. If boron is deposited directly on a carbon fiber, the elongation of the growing fiber tends to break the carbon fiber into short sections. Hot spots are produced at these breaks due to the redistribution of the heating current through the higher resistance of the boron. In the production of the B/C fibers at AVCO, this problem has been solved by coating the 33 μm diameter carbon fiber with a thin layer of pyrolytic graphite 1.3 μm thick. This layer has a sufficiently small shear strength to decouple mechanically the elongating boron from the carbon core and prevent breaking of the core.

The longitudinal residual stress distribution was calculated from measurements of the change in length of the fiber produced by removal of the surface by electropolishing. A complete description of this method is given in reference 6. Briefly a 1 cm long section of the fiber to be tested was mounted in a gauge which allowed a continuous record of the fiber's length vs. time to be made. The surface of the fiber was removed by electropolishing at a known rate. From these data a plot of longitudinal strain, ϵ_z , vs fiber radius, r , was made. From the ϵ_z vs r data, the longitudinal residual stress, σ_z , as a function of r could be calculated from the equation (ref. 6)

$$\sigma(r_0, r) = - \left[(E_c - E_b) \frac{r_c^2}{r^2} + E_b \right] \times \left[\frac{r}{2} \frac{d\epsilon_z(r)}{dr} + \epsilon_z(r) \right] \quad (1)$$

where

$\epsilon(r_0, r)$ is the strain at a position r in the as-received fiber of radius r_0 .

E_c is the Young's modulus of the core.

E_b is the Young's modulus of the boron sheath.

r_c is the radius of the core with modulus E_c .

r is the radius of the electropolished fiber.

$\epsilon_z(r)$ is the axial strain when the fiber is electropolished to a radius, r , with $\epsilon_z(r_0) = 0$.

RESULTS AND DISCUSSION

Five or more separate runs were made on B/W and B/C fibers. In all the runs using the B/C fibers, measurements were made up to the carbon core. In the case of the B/W fibers, this was possible in only one of the runs because of fiber breakage. Figure 1 is a plot of the longitudinal strain, $\epsilon_z(r)$, vs the electropolished radius, r , for typical 102 μm diameter B/W and B/C fibers. Both fiber types showed an initial contraction. As the electropolishing continued, they both ceased to contract and began to elongate near a fiber radius of 44 μm . At the core surfaces the strains are positive for the B/W fibers and negative for the B/C fibers.

With equation (1) the strains can be used to determine the residual longitudinal stresses. In the case of B/W, DiCarlo (ref. 8) has shown that the core consists of two tungsten borides; an inner part of W_2B_5 , about 12.8 μm in diameter, and an outer part of WB_4 , 17 μm in diameter. He reports average Young's moduli of the two core borides and the boron sheath to be 669 GN/m^2 for the W_2B_5 , 407 GN/m^2 for the WB_4 , and 393 GN/m^2 for the boron sheath. In equation (1) we consider the outer core of WB_4 and the boron sheath to have the same Young's moduli. Then

$$E_c = 669 \text{ GN/m}^2$$

$$E_b = 393 \text{ GN/m}^2$$

$$r_c = 6.4 \mu\text{m}$$

for the B/W fibers. For the B/C fibers the following values were used:

$$E_c = 41 \text{ GN/m}^2$$

$$E_b = 393 \text{ GN/m}^2$$

$$r_c = 19 \mu\text{m}$$

Figure 2 is a plot of the longitudinal residual stresses calculated by using equation 1 and the data shown in figure 1. Both the B/W and B/C curves show the residual stresses are compressive at the surface and pass through zero stress near r equal to 38 μm . For the B/W fibers the stress increases in

tension to a maximum near 1020 MN/m^2 and then passes through zero stress to an average compressive stress in the core of -1330 MN/m^2 . The curve for the B/C fibers shows quite a different behavior. After reaching a maximum tension stress of 450 MN/m^2 the stress drops rapidly with decreasing radius to a compressive stress of -1160 MN/m^2 and then, changing sign, to an average tension stress in the carbon core of 81 MN/m^2 . This core stress reflects the shear strength of the pyrolytic graphite coating.

In figure 3 is shown a reproduction of a scanning electron micrograph (magnification of 1000X) of the B/W core after electropolishing has removed the boron sheath. Two regions can be noted; the intact core which has a diameter of $16.3 \mu\text{m}$, and a second region where the core surface has broken away, probably due to handling after electropolishing. The outer diameter corresponds roughly with the outer diameter of the WB_4 tungsten boride reported by DiCarlo (ref. 7). Also in this figure the die drawing marks of the original tungsten wire can be seen in the borided core as the striations running longitudinally along the core.

Figure 4 is a reproduction of a scanning electron micrograph (magnification 1000X) of the carbon core after removal of the boron by electropolishing. Three distinct regions can be seen. The region with the smallest diameter of $33 \mu\text{m}$ corresponds to the original carbon fiber. The next region has a diameter of $36 \mu\text{m}$ which corresponds to the diameter of the original carbon fiber after coating with the pyrolytic graphite. The third region which made up most of the length of the specimen had a diameter of $38 \mu\text{m}$. This layer is most likely produced by a slight interdiffusion of boron and the pyrolytic graphite.

These findings are of interest not only because they contribute to an understanding of the factors which limit the strength of boron fibers, but also because of the possibility that this knowledge can be used to significantly increase the strength and impact energy absorption of these fibers. In the case of B/W fibers, the strength limiting flaws are located at the surface and in the core. The surface flaws can be removed by chemical etching as shown by Smith (ref. 1). The removal of the core flaws is a somewhat harder task; however, the strength could be increased if the residual compressive stress in the core could be increased. This might be possible through changes in the fiber production process. Such a possibility is currently being studied. In the case of the B/C fibers, the situation is not quite as clear due mainly to the lack of information concerning flaw location.

SUMMARY

Residual stresses are one of the factors which influence the fracture strength of brittle materials such as boron deposited on tungsten or carbon by chemical vapor deposition. We have measured the longitudinal residual stress distribution for both 102 μm (4 mil) diameter boron on tungsten, B/W, and boron on carbon, B/C, fibers. The stress distributions were calculated from measurements of changes in the lengths of the fibers produced by surface removal by an electropolishing method. For both types of fibers, the residual stress varied from a compressive stress of approximately -1300 MN/m^2 (188 ksi) at the surface to tensile stress in the boron near the core. This stress for the B/W was approximately 1020 MN/m^2 (148 ksi) and for the B/C it was approximately 450 MN/m^2 (65 ksi). Closer to the core and in the core significant differences in the residual stresses were observed for the B/W and B/C fibers.

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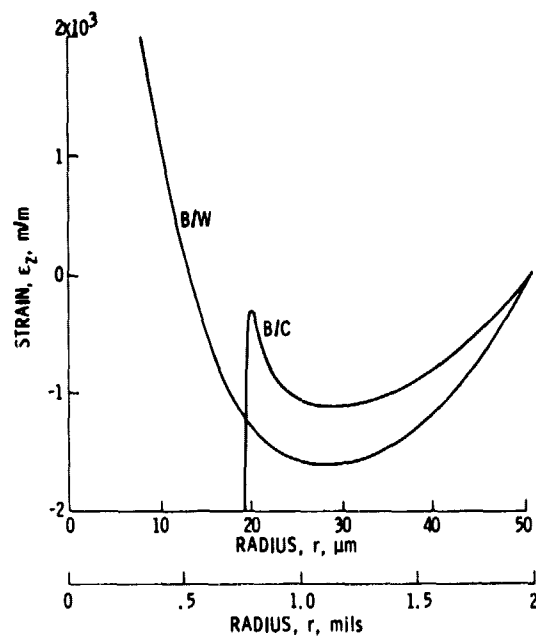


Figure 1. - Longitudinal strain ϵ_z for B/W and B/C fibers produced by electropolishing the fiber to a radius of r .

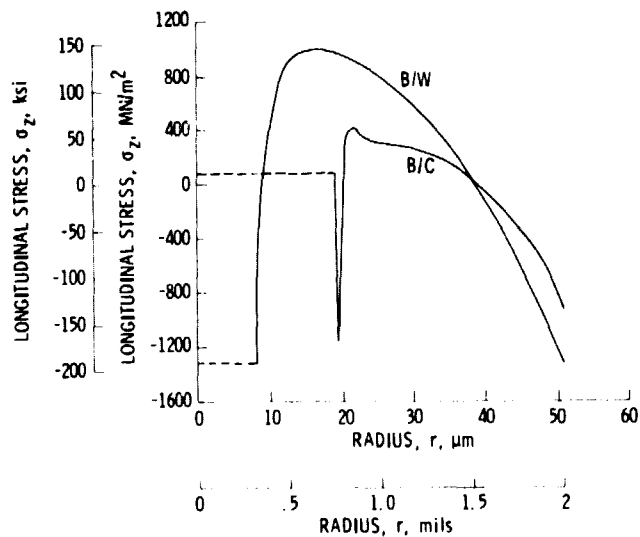


Figure 2. - Longitudinal residual stress distribution $\sigma_z(r, r)$ at a position r from the fiber center in the as-received fiber.



Figure 3. - Scanning electron micrograph of tungsten boride core after complete removal of boron sheath by electropolishing of B/W 102 μm (4 mil) diameter fiber. X1000.

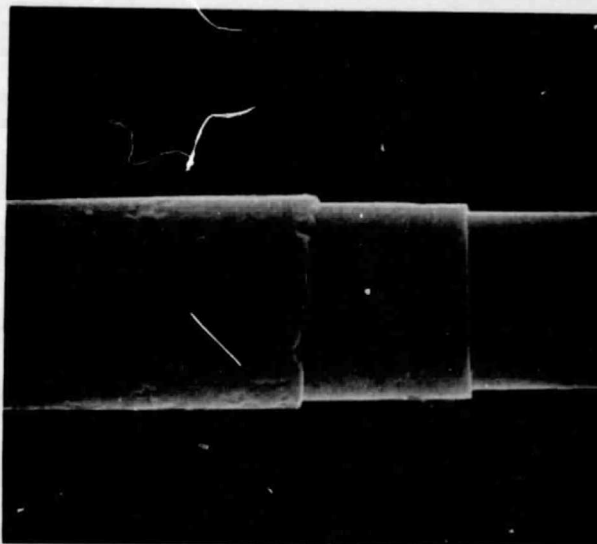


Figure 4. - Scanning electron micrograph of carbon core after complete removal of boron sheath by electropolishing of B/C 102 μm (4 mil) diameter fiber. X1000.